Fermilab

Particle Physics Division
Mechanical Department Engineering Note

MD-ENG-380

Number: PPD doc-1347 Date: April 4, 2011

Project: CMS Upgrade Cooling System Test Design

Title: CMS CO_2 Test Stand Piping Note

Author(s): Erik Voirin

Reviewer(s): Andy Stefanik

Key Words: Piping note, 31.3, ASME, 5031

Abstract Summary:

The CMS CO_2 Detector test stand uses commercial refrigeration units which run from to the heat exchangers in the storage tank suspended in Lab C. This document serves to provide details on the piping system and its components. The design pressure of lowest part of the piping system is the suction side of the chillers themselves, which is 178 psig. This piping note analyzes the piping and all components and shows everything in the system is rated for the design pressure and stress does not exceed the amount allowed by ASME 31.3 code for process piping.

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Chapter:

1. FESHM 5031.1 PIPING ENGINEERING NOTE FORM

Prepared by: **Erik Voirin** Preparation Date: **5-26-2011**

Piping System Title: **CMS CO_2 Cooling Test Stand – Copper Pipes**

Lab Location: **Lab C** Location code: **604**

Purpose of system**: Cool the Carbon Dioxide in the Storage Tank via heat exchangers**

Piping System ID Number: **none assigned to date**

Appropriate governing piping code: **ASHRAE 15 and ASME B31.5 – FESHM 5031.1 lists 31.3 as the applicable code**

Fluid Service Category (if B31.3): **ASME 31.3 Lists Normal Fluid Service ASHRAE 15 lists as category A-1**

Fluid Contents: **R-404a**

Design Pressure: **300 psi suction (lowside) – 450 psi supply (highside)**

Piping Materials: **Drawn Copper tube (Type K) and ¼" annealed copper tubing**

Drawing Numbers (PID's, weldments, etc.): **9212-750-ME-466879**

Designer/Manufacturer: **Fermilab**

Test Pressure: **300 psig** Test Fluid: **Nitrogen** Test Date: **May 26, 2011**

Statements of Compliance

Piping system conforms to FESHM 5031.1, installation ***is not*** exceptional: **Yes**

Piping system conforms to FESHM 5031.1, installation ***is*** exceptional and has been designed, fabricated, inspected, and tested using sound engineering principles: **N/A**

Reviewed by: ______________________________ (Print Name)

Signature: ______________________________Date: __________

D/S Head's Signature: ________________________Date: __________

The following signatures are required for exceptional piping systems:

ES&H Director's Signature: _____________________Date: __________

Director's Signature or Designee: __________________Date: __________

Pipe Characteristics

Size**: 1/4"OD x 0.03” tube and Type K tube: OD: 3/8”, 1/2”, 7/8” and 1-3/8”**

Volume: **<1 Gal**

Relief Valve Information:

Type: **Burst Disk x 2** Manufacturer: **BS&B Safety Systems**

Set Pressure: **425 psig @ 72F** Relief Capacity: **0.19 in^2 size – 13902 lb/hr**

Type: **Spring** Manufacturer: **Kingston**

Set Pressure: **300 psig @ 72F** Relief Capacity: **369 SCFM**

Relief Design Code: **ASME Section VIII (UD stamped) & Section III**

Is the system designed to meet the identified governing code? **Yes – ASHRAE 15**

Fabrication Quality Verification:

Process and Instrumentation diagram appended? **Yes**

Process and Instrumentation component list appended? **Yes**

Is an operating procedure necessary for safe operation? **No**

If ‘yes’, procedure must be appended.

Exceptional Piping System

Is the piping system or any part of it in the above category? **No**

If “Yes”, follow the requirements for an extended engineering note for Exceptional Piping Systems.

Quality Assurance

List vendor(s) for assemblies welded/brazed off site: **None**

List welder(s) for assemblies welded/brazed in-house:

(Abraham Diaz – PPD Technician)

Append welder qualification Records for in-house welded/brazed assemblies. **N/A**

AHSRAE 15 makes no mention of qualifications for brazing refrigeration piping, (nor does Fermilab test or qualify personnel in brazing). The technician who performed the brazing was previously employed as a refrigeration technician and has 5 years of experience brazing copper piping for commercial and industrial air conditioning and refrigeration systems.

Append all quality verification records required by the identified code (e.g. examiner's certification, inspector's certification, test records, etc.) **Yes**

2. Description and Identification

The copper piping in the CMS CO_2 Cooling Test stand is a closed loop system which connects three purchased commercial chillers to the heat exchangers housed in the CO_2 storage tank of the cooling system. A piping note for the piping on the CO_2 side is in a separate piping note: https://ppd-docdb.fnal.gov:440/cgi-bin/ShowDocument?docid=1347. A system overview can be seem in Fig.1, which is drawn spatially similar to the piping and instrument diagram which is attached for reference on the following page. This piping note for the CO_2 cooling system is specific to the copper pipes containing the R-404a refrigerant which connect the chilling units and the CO_2 storage tank. Figure 2 on the following page shows the relevant parts of the P&ID which contains the copper refrigeration piping.

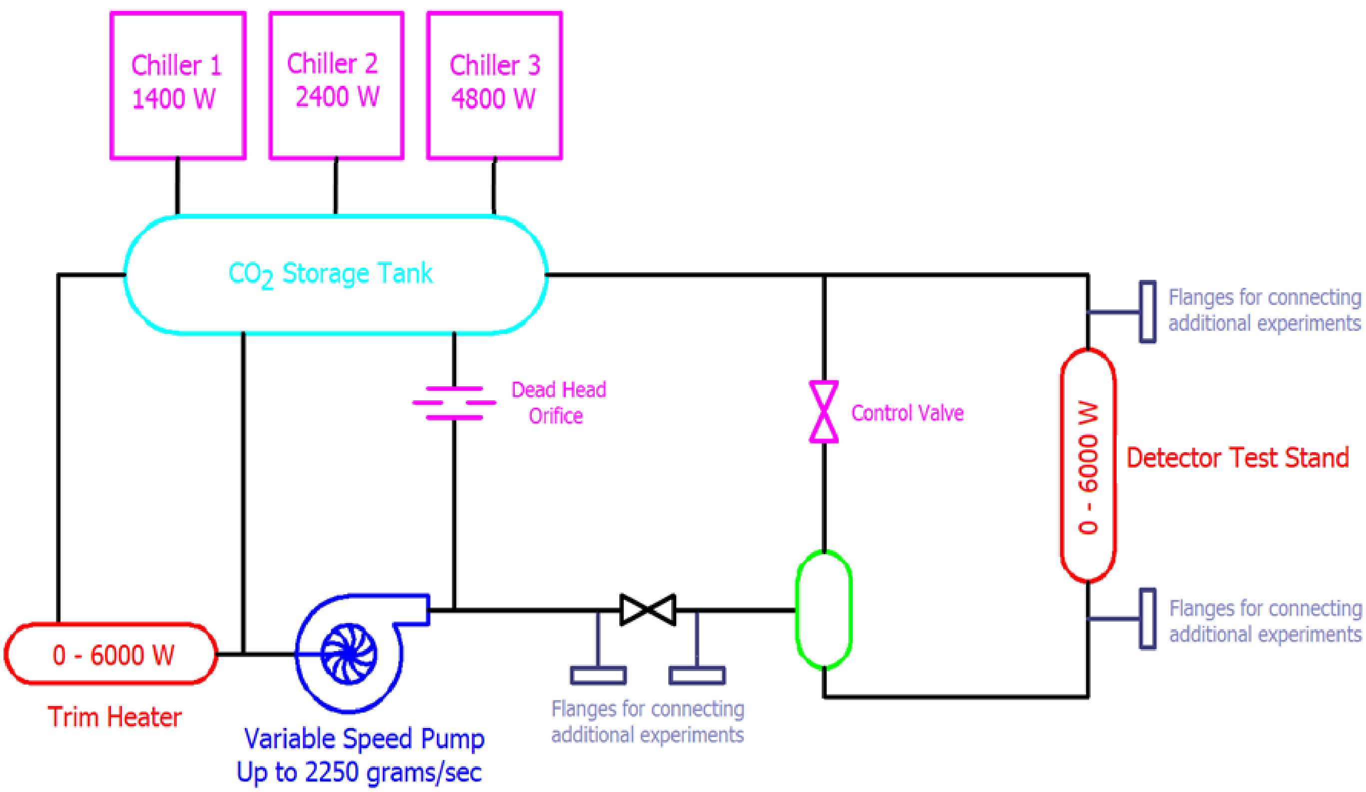


Figure 1: CMS CO2 test stand cooling system overview.

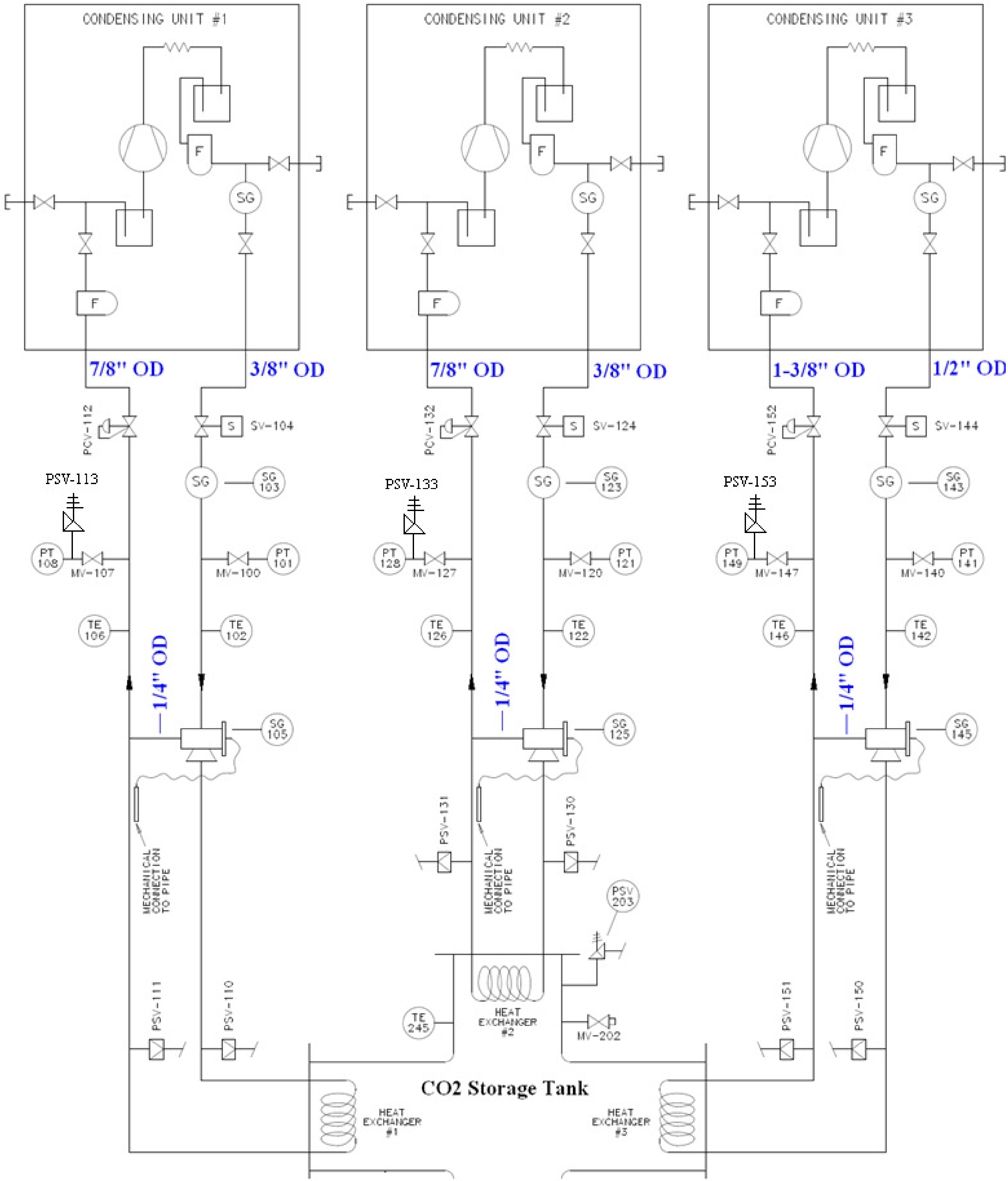


Figure 2: Relevant area of system P&ID (copper refrigeration route)

3. Design Verification

The CMS copper refrigeration piping meets the requirements of Section 5031.1 of the Fermilab ES&H Manual http://esh-docdb.fnal.gov/cgi-bin/RetrieveFile?docid=362&version=7&filename=5031.1.pdf. This section states in Table 1: Refrigerant for process piping system falls under the ASME 31.3 code for process piping, and refrigerant for HVAC (which includes walk in freezers) is covered under ASME 31.5. The scope of both 31.3 and 31.5 are listed below, referenced from ASME.[4]

B31.3 Process Piping: piping typically found in process facilities such as petroleum refineries, chemical, pharmaceutical, textile, paper, semiconductor, and cryogenic plants, and related processing plants and terminals. B31.3 is intended to be applied to:

- *Piping for all fluid services*
- *Metallic and nonmetallic piping*
- *All pressures*
- *All temperatures*

B31.5 Refrigeration Piping and Heat Transfer Components: piping and heat transfer components containing refrigerants and secondary coolants including water when water is used as a secondary coolant. B31.5 is intended to be applied to:

- *Refrigerant and secondary coolant piping*
- *Heat transfer components such as condensers and evaporators*
- *All pressures*
- *Temperatures at and above -320°F (-196°C)*

The piping system connects the heat exchangers, which fall under the scope of ASHRAE 15/ASME 31.5, not 31.3, to the standard commercial package refrigeration units. These unaltered commercial condensing units contain heat transfer components which fall under the scope of ASHRAE 15 and ASME 31.5, not 31.3. While not wrong to cover the piping under the more general code 31.3, the design engineer believes the more specific and appropriate code for this specific piping system is ASHRAE 15 and ASME 31.5. The condensing units are designed for use in a commercial walk in deep freezer (covered by ASME 31.5 and ASHRAE 15), and are unaltered and have no service difference other than being turned on and off by a programmable logic controller sensing temperature and choosing on/off cycles rather than a thermostat. Table 1 of FESHM 5031.1 is also titled to be applicable code *guidance*, not applicable code *directives,* so the more specific ASHRAE 15 will be followed in this particular piping design. Though, the only major differences are the pressure test procedures, brazing qualifications, and ASHRAE 15 requiring an ODH analysis as part of the system design.

Materials:

The piping is fabricated from copper. The lowest allowable stress for drawn copper tubing 10,300 psi, given by the Copper Tube Handbook, which is referenced as a competent source in ASME 31.3 Paragraph 333.4.1.[2] However, this reference also states the allowable stress for annealed copper must be used for pipe lengths if the joints were brazed due to the possibility of annealing the joint during brazing. The lines comprised of 4 different sizes of type K copper tubing with outer diameters of 3/8", 1/2", 7/8", and 1-3/8". There is also a small amount of ¼" OD by 0.030 wall copper tube connecting the thermostatic expansion valves. The condensing unit manufacturer suggested these line sizes and type L copper tube, however type K has a thicker wall and is therefore a more conservative choice.

The piping will be operated at -40C (-40F) minimum. This is above the minimum temperature listed for copper pipe or tube. Copper Pipe is the standard material used in refrigeration systems similar to this one, and the chilling unit manufacturer listed copper pipe/tube as the only material to be used in system piping. Copper fittings are standard copper fittings for refrigeration and water tubing. Copper fittings are standard to all types (L, M, K) of copper tube and are pressure rated by the manufacturer.

Stress analysis:

Calculations were done for pipe stress due to internal pressure. Refrigeration industry standard recommendations[2] for pipe supports of every 8 feet for horizontal runs and 10 feet for vertical runs were adhered to as well. The design uses standard copper tubing and fittings, which is the general practice, as well as the only choice, for this type of refrigeration piping system.

The piping system contains five sizes of copper pipe/tube, they are:

1. 1/4" OD x 0.030" tubing
2. Type K Tube 3/8" OD
3. Type K Tube 1/2" OD
4. Type K Tube 7-8" OD
5. Type K Tube 1-3/8" OD

Calculations for the maximum allowable internal pressure for these pipe sizes are as calculated per the following equation:

American Society of Mechanical Engineers Code for Pressure Piping (ASME B31):

$$P = \frac{2S(t_{min} - C)}{D_{max} - 0.8\,(t_{min} - C)}$$

where:
P = allowable pressure, psi
S = maximum allowable stress in tension, psi
t_{min} = wall thickness (min.), in.
D_{max} = outside diameter (max.), in.
C = a constant

Allowable stress for drawn tubing is 10,300 psi, however the allowable stress value for annealed tube (6000 psi) must be used when joints are brazed since the brazing involves heating the joints and possibly annealing the piping.[2] B31 permits the constant “C” to be zero due to copper's excellent resistance to corrosion. Due to manufacturing tolerances the diameter and thickness may not be exact. With the same internal pressure, stress increases with an increasing outer diameter and a decreasing wall thickness. For a worst case scenario we will assume the pipes tolerances are plus or minus 12.5% on the wall thickness and outer diameter. Today’s tube drawing methods will yield products much better than this, most OD tolerances for copper tube are around plus or minus 0.003" but the calculation is conservative and still shows the piping is more than adequate to hold the pressure. Calculations for pipe sizes 1 through 5 are as follows:

$$D := \begin{pmatrix} 0.25 \\ 0.375 \\ .5 \\ .875 \\ 1.375 \end{pmatrix} \text{in} \qquad t := \begin{pmatrix} 0.030 \\ 0.035 \\ 0.049 \\ 0.065 \\ 0.065 \end{pmatrix} \text{in} \qquad \begin{array}{l} S := 6000\text{psi} \\ C := 0 \end{array}$$

$$D_{max} := D\cdot(1 + 12.5\%) \qquad t_{min} := t\cdot(1 - 12.5\%)$$

$$P := \frac{2\cdot S\cdot\left(t_{min} - C\right)}{D_{max} - 0.8\left(t_{min} - C\right)} = \begin{pmatrix} 1210 \\ 925 \\ 974 \\ 727 \\ 455 \end{pmatrix} \text{psi}$$

These results show the pressure ratings are higher than the design pressure of the system which is 400 psi on the highside, and 300 psi on the lowside.

4. Pressure Containment / Relief System

Relief Valves:

Each of the six applicable piping areas are equipped with a burst disk set to 425 psi @ 72F. The minimum opening for these burst disks is 0.19 in^2. All burst disks are ½" NPT BS&B Safety Systems A6 FRB Sta-Kul Rupture Disk Assemblies. The Disk Material is 316SS. These burst disks have been manufacturer tested in accordance with ASME Section VIII (UD stamped) & Section III. For Burst Disk numbers and specific locations see the Piping and Instrument Diagram. Calculations were performed which show the capacity of these valves more than meet the criteria of API 521 and ASME standards for worst case overpressure scenario of a fire case. Details of these calculations were performed in accordance with API 521 and CGA-S-1.3 2005. Since the MAWP of the piping and all system components is rated to a minimum 400 psig, which is the saturation pressure of the refrigerant at 139^{o}F, the only reasonable overpressure scenarios are an entire building fire case, or a split tube in the CO_2 heat exchanger. The installed rupture disks are capable of providing the adequate relieving capacity in both scenarios, calculations shown in Appendix A.

In case of very slow evaporator leaks which could allow high pressure CO2 to enter the system slow enough to leak through the crankcase pressure regulating valve and into the condensing unit, there are also spring type relief valves on the suction side which are set to 300 psi and will protect the system in this failure scenario. The Minimum operating pressure of any component in these condensing units are the compressors is 320 psi, MAWP may be more.

5. Brazing Information

Brazing of copper to copper joints was performed using "Sil-Phos" phosphorus containing, 15% silver content brazing rod. This exceeds the requirements set in ASHRAE 15 Paragraph 9.13.2 which states joints on refrigerant containing copper tube that are made by the addition of filler metal must be brazed with the exception of A-1 refrigerants. For A-1 refrigerants soldering is sufficient for all pipe joints.

Procedures used for brazing joints:

A. When brazing, remove solenoid-valve coils and sight glasses; also remove valve stems, seats, and packing, and accessible internal parts of refrigerant specialties. Do not apply heat near expansion valve bulb. Joints shall be cool before reassembling valve.

B. Tubing shall be cut square, reamed, and burrs removed.

C. Both inside of fittings and outside of tubing shall be well cleaned with an abrasive cloth or stainless-steel wire brush before brazing. Steel wool is NOT permitted.

D. Care shall be taken to prevent annealing of fittings and tubing when making connections. (Pipe stress calculations have used the conservative annealed strength so annealing will not deem the adjacent pipe unsafe regardless)

E. Copper to copper joints shall be brazed with a copper-phosphorous brazing alloy containing a minimum of 15% silver and conforming to AWS A5.8, BCuP5.

F. Copper to brass joints shall be brazed with a silver brazing alloy containing a minimum of 50% silver and conforms to AWS 5.8, BAg-7.

G. Copper to stainless steel joints shall be brazed with a silver brazing alloy containing a minimum of 50% silver and conforms to AWS 5.8, BAg-7.

H. All brazed joints shall be cleaned to remove residual flux.

I. A visual inspection shall be performed to check for proper filling and filleting of the braze material.

6. <u>Brazing Qualifications</u>

Not Applicable - AHSRAE 15 makes no mention of qualifications for brazing refrigeration piping, nor does Fermilab test or certify for brazing. ASME 31.3 paragraph 333.1.1 states requirements for brazer certification are at the owners option. The PPD technician who performed the brazing (Abraham Diaz) was previously employed as a refrigeration technician and has 5 years of experience brazing copper piping for commercial and industrial air conditioning and refrigeration systems.

7. Inspection Plan / Examiners Report

In accordance with ASHRAE 15 Paragraph 8.9, Refrigerant pipe joints erected on the premises shall be exposed to view for visual inspection prior to being covered or enclosed.   All joints are lest exposed and were visually checked immediately after brazing. All joints were then again visually inspected, then bubble tested during the pressure test before being covered with insulation. The pressure test will be performed in accordance with ASHRAE 15 will demonstrate the integrity of the pipe and its components.

8. Component Identification

Process and Instrument diagram:

The process and instrument diagram is on drawing 9212.750-ME-466879, and also included in Figure 2 on Page 6. This diagram is followed by the valve and instrument list.

Piping components:

The following is a list of the piping system components for each of the closed loop refrigeration systems and their pressure ratings. Components for condensing unit #1 are seen in Table #1, while components for condensing units #2 and #3 follow the same Table numbering scheme.

Table 1: Piping system components for condensing unit #1.

Condensing Unit #1					
Type	number	Instrument Type	Model#	Pressure Rating	Distributor
MV	100	Manual shutoff Valve	47865K21	450 psi	McMaster
PT	101	Pressure transmitter	C207	1000psi	Setra
TE	102	Surface mount Temp. Elem.	PT100	N/A	InTempco
SG	103	Sight glass	HMI-1TT3	680 psi	Emerson Climate
SV	104	solenoid valve	100RB	500 psi	Emerson Climate
SG	105	Expansion valve	CE-A-SX35	500 psi	Emerson Climate
TE	106	Surface mount Temp. Elem.	PT100	N/A	InTempco
MV	107	Manual shutoff valve	47865K21	450 psi	McMaster
PT	108	Pressure transmitter	C207	1000psi	Setra
PSV	110	Burst disc - vent to atm	A-6 FRB	425 psi	BS&B Safety
PSV	111	Burst disc - vent to atm	A-6 FRB	425 psi	BS&B Safety
PCV	112	Crankcase Regulating Valve	Crot-10-0/60	400 psi	Sporlan

Table 2: Piping system components for condensing unit #2.

Condensing Unit #2					
Type	number	Instrument Type	Model#	Pressure Rating	Distributor
MV	120	Manual shutoff Valve	47865K21	450 psi	McMaster
PT	121	Pressure transmitter	C207	1000psi	Setra
TE	122	Surface mount Temp. Elem.	PT100	N/A	InTempco
SG	123	Sight glass	HMI-1TT3	680 psi	Emerson Climate
SV	124	solenoid valve	100RB	500 psi	Emerson Climate
SG	125	Expansion valve	CE-C-SX35	500 psi	Emerson Climate
TE	126	Surface mount Temp. Elem.	PT100	N/A	InTempco
MV	127	Manual shutoff valve	47865K21	450 psi	McMaster
PT	128	Pressure transmitter	C207	1000psi	Setra
PSV	130	Burst disc - vent to atm	A-6 FRB	425 psi	BS&B Safety
PSV	131	Burst disc - vent to atm	A-6 FRB	425 psi	BS&B Safety
PCV	132	Crankcase Regulating Valve	Crot-10-0/60	400 psi	Sporlan

Table 3: Piping system components for condensing unit #3.

Condensing Unit #3					
Type	number	Instrument Type	Model#	Pressure Rating	Distributor
MV	140	Manual shutoff Valve	47865K21	450 psi	McMaster
PT	141	Pressure transmitter	C207	1000psi	Setra
TE	142	Surface mount Temp. Elem.	PT100	N/A	InTempco
SG	143	Sight glass	HMI-1TT4	680 psi	Emerson Climate
SV	144	solenoid valve	100RB	500 psi	Emerson Climate
SG	145	Expansion valve	CE-C-SX35	500 psi	Emerson Climate
TE	146	Surface mount Temp. Elem.	PT100	N/A	InTempco
MV	147	Manual shutoff valve	47865K21	450 psi	McMaster
PT	149	Pressure transmitter	C207	1000psi	Setra
PSV	150	Burst disc - vent to atm	A-6 FRB	425 psi	BS&B Safety
PSV	151	Burst disc - vent to atm	A-6 FRB	425 psi	BS&B Safety
PCV	152	Crankcase Regulating Valve	Crot-10-0/60	400 psi	Sporlan

As previously stated, the tubing used was standard Type K Copper tubing, this was purchased from the Fermilab stockroom. The copper tube fittings are also standard copper fittings acquired from the Fermilab stockroom and McMaster-Carr. The copper fittings are listed as having a pressure rating of 500 psi for sizes 1" and below, and the fittings 1-1/4" and larger are listed as having a 400 psi pressure rating. One may notice the largest fittings and the Crankcase Regulating Valves have a MAWP of 400 psi while the burst disks are set to release pressure at 425 psi, which is above the MAWP of the lowest rated components. These burst disks are rated at 425 psi at 72^{o}F, but the rupture pressure decreases with decreasing temperature according to Figure 3. We can see in Figure 4 (data obtained from RefProp v9.0), the saturation temperature of the refrigerant at 400 psig is ~60C. Back to Figure 3, at 60C our 316SS disk is de-rated to 94% of its setting, or 399.5 psi. The system is also equipped with 300 psi relief valves on the suction sides for slow leaks through the evaporator which may leak high pressure CO_2 into the copper piping system.

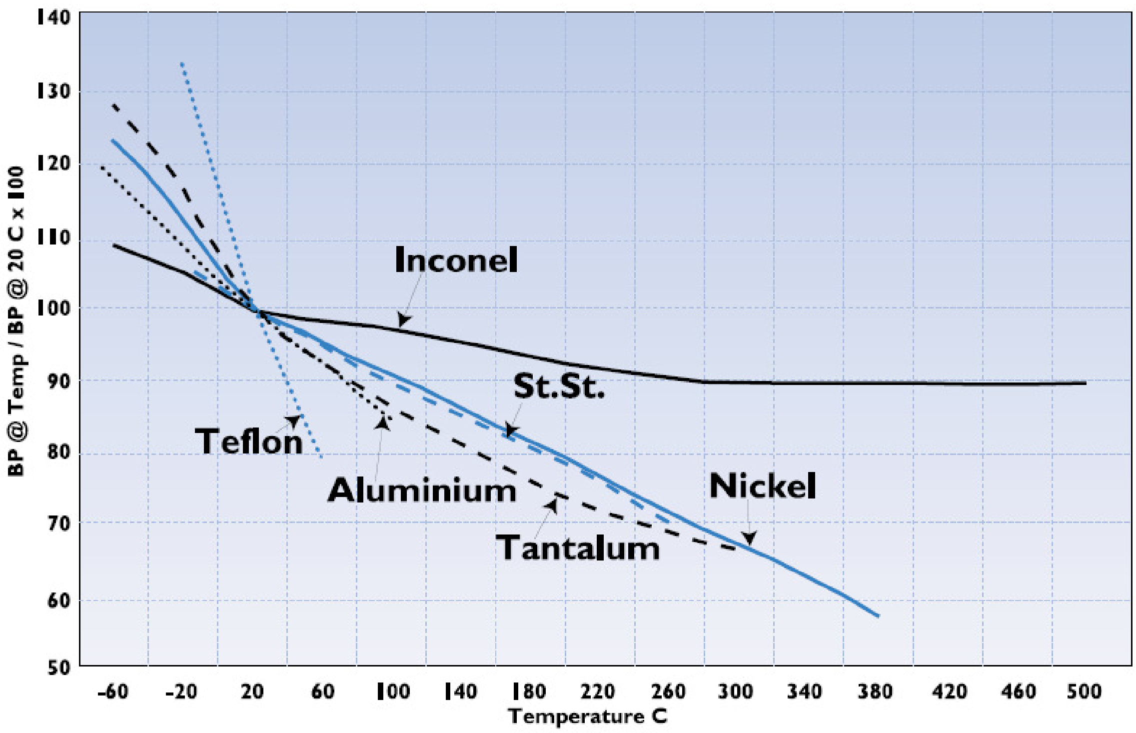


Figure 3: Rupture Pressure vs. Temperature for numerous Burst Disk materials [3]

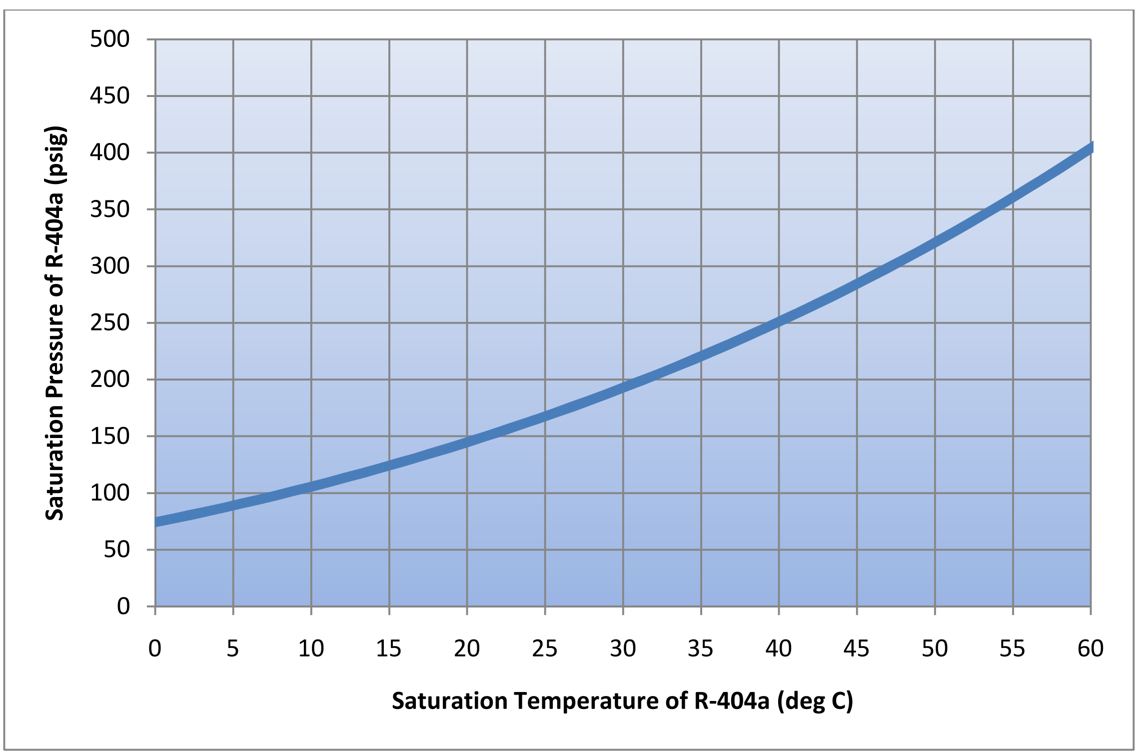


Figure 4: Saturation curve for R-404a (Data obtained from RefProp v9.0)

9. Leak / Pressure Test Procedures

The Highside design is 450 psig, and the Lowside design pressure of the refrigeration units is listed as 300 psig. This information can be found in the product literature as well as stamped on the units themselves. Since the chilling units themselves are purchased commercial packages, and have already been tested by the manufacturer they will not be retested, which is allowed in ASHRAE 15. The changeover parts of the system, what separates the highside from lowside are the compressor, which raises the pressure, and the thermostatic expansion valve, which lowers the pressure. The condensing units have procedures for leak checking the piping system which are different (less stringent) from those listed in ASHRAE 15. The most stringent pressure testing procedures relevant to this system will be used to assure safety. Since this involves testing at higher pressures than the maximum listed by the chilling unit manufacturer (150 psi), these chilling units will be blocked off with valves as to only test the copper piping system connected to these chilling units. Therefore, only piping installed by Fermilab technicians, which is connected to these chilling units, will be pressure tested according to procedures listed in ASHRAE 15 which state in paragraph 10.1.1:

> "The highside and lowside of each system shall be tested and proved tight at not less than the lower of the design pressure or the setting of the pressure-relief device protecting the highside or lowside of the system, respectively."

Paragraph 10.1.2 (d) provides and field test exception reading:

> "Systems erected on the premises using Group A1 refrigerant and with copper tubing not exceeding 0.62 in. (16 mm) outside diameter shall be tested by means of the refrigerant charged into the system at the saturated vapor pressure of the refrigerant at 68°F (20°C) minimum."

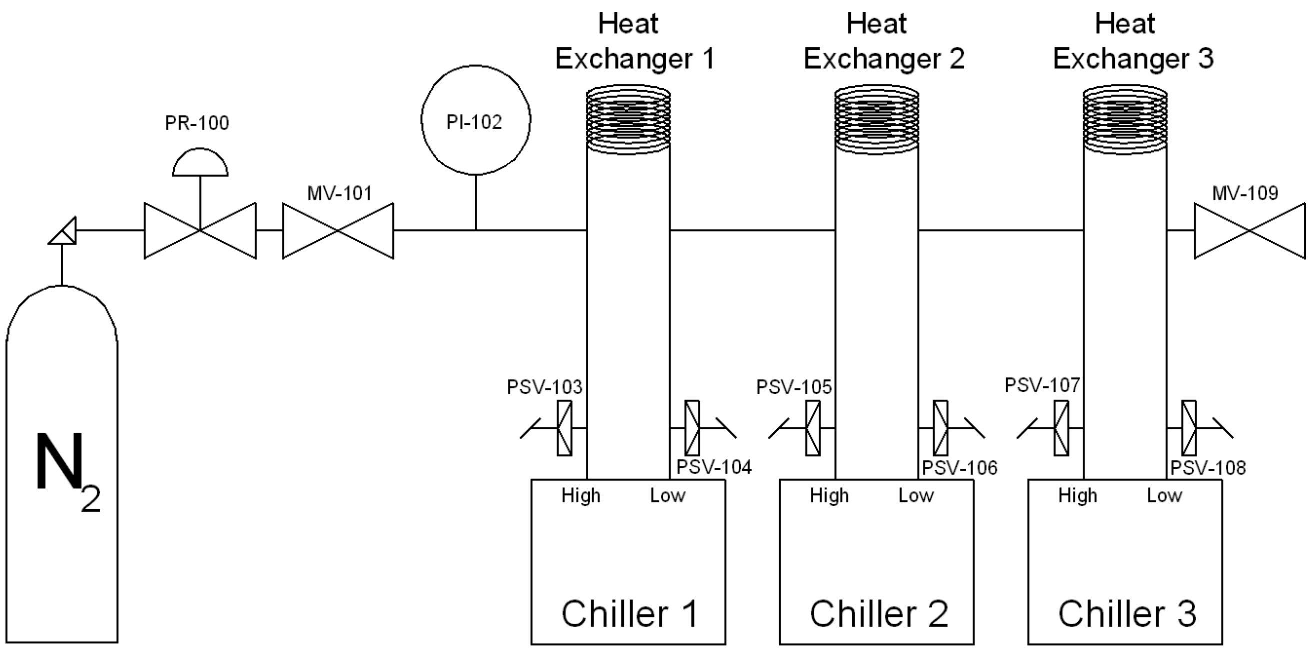
Piping sizes for the three units are sized per manufacturer specs and are as follows:

- Small Chiller:
    - Highside: 3/8” OD
    - Lowside: 7/8” OD
- Medium Chiller:
    - Highside: 3/8” OD
    - Lowside: 7/8” OD
- Large Chiller:
    - Highside: 1/2” OD
    - Lowside: 1-3/8” OD

Therefore the highside piping for each chiller can be pressure tested during the initial fill of the refrigerant according to the exception listed in paragraph 10.1.2 (d). The lowside piping is larger than 0.62” OD for all three chillers and must be pressure tested at 300 psi, which is the lower of the design pressure (300 psi) or the setting of the pressure-relief device protecting the lowside of the system (300 psi). The highside will be raised to the same pressure as the lowside during the lowside pressure test for a preliminary leak check before what would be the “initial service pressure test”. The saturation pressure of the refrigerant R-404a is 159 psia (145 psig) at the 68F minimum initial service pressure test temperature. This means the initial lowside pressure test at 300 psig is more stringent than the initial service test, and can constitute as the pressure test for the high side as well. Therefore both the highside and lowside of the system will be leak and pressure tested simultaneously at a pressure of 25 psi (leak check) and 300 psig (pressure test).

Testing Procedures:

The CMS CO_2 Piping Network will be leak checked and pressure tested in accordance with FESHM 5034 and ASHRAE 15. The layout of the pressure test will be as in the diagram below.



The nitrogen supply cylinder will be connected to the refrigeration piping by a ¼" copper tube. The cylinder will contain a nitrogen pressure regulator, then a manual valve (MV-101) for throttling flow. The manual valve is a ¼" Swagelok SS-4P4T4 Valve rated at 3000 psi. The testing system will also have a pressure gauge (PI-102) just after the manual valve. This pressure gauge will have copper tubing which will route to the refrigeration piping and attach to a ¼" NPT to tube fitting on the piping network. The piping systems will be joined together with ¼" copper tubing for the pressure test so all three piping systems can be checked simultaneously. ASHRAE 15 makes no mention of relief valves being required during the pressure test, though the systems two burst disks will be in place during the test regardless.

Pressure Step 1: 25 psi

Pressurization will begin by setting the pressure regulator (PR-100) to 25 psi and slowly opening MV-101, pressurizing to 25 psi as given by PI-102. At this time MV-101 will then be closed and the system pressure monitored for pressure holding in an attempt to find gross leaks. After 5 minutes, testers will visually/audibly check all brazed joints, NPT connections, and other components for leaks. PI-102 will again be observed to monitor for consistent pressure level.

Pressure Step 2: 300 psi

If no leaks are found, the pressure regulator will be set to 300 psi and MV-101 slowly opened. The pressure will be raised slowly to 300 psi. Then MV-101 will be closed and the pressure held for 10 minutes monitoring the system pressure for changes via PI-102. If the pressure decreases, implying a leak, the system pressure will be reduced by throttling MV-109 back to pressure step 1 (25 psi) where a bubble test using Snoop or a similar product will be performed in an attempt to locate the leak. If the pressure read from PI-102 is consistent for 10 minutes, the cylinder will be closed, and examiners will bubble test using Snoop or a similar product. If all brazed joints, NPT connections, and other components pass the visual inspection, bubble test, and the reading of PI-102 has not decreased, the system will be considered to pass the leak and pressure test.

Relieving Pressure

MV-109 will be slowly opened and the system pressure slowly decreased back to atmospheric.

10. ODH / Quantity of Refrigerant per Occupied Space

ASHREA 15 Table 1 Lists the Maximum refrigerant per occupied space as 60,000 ppm or 6%. A sudden total release of all three charges of R-404a, 56 lbs total, yields only 3000 ppm, or 0.3% contamination, which is below the allowable limit; calculations follow

Mass in three system charges

$$mass_{R404} := 28lb + 14lb \cdot 2 = 56\,lb$$

Volume of Lab C

$$Vol_{LabC} := 73000ft^3$$

Density of R404a (STP)

$$\rho_{404STD} := 3.9206\,\frac{kg}{m^3}$$

Mass in three system charges

$$Volume_{R404} := \frac{mass_{R404}}{\rho_{404STD}} = 228.8\,ft^3$$

Contamination Percentage

$$Contamination := \frac{Volume_{R404}}{Vol_{LabC}} = 0.313\,\%$$

Date: April 28, 2011

EXHIBIT B
Pressure Testing Permit*

Type of Test: [ ]Hydrostatic [X] Pneumatic

Test Pressure **300 psig** Minimum Components MAWP **400 psig**

Items to be Tested: **Copper Pipe for refrigeration lines on CO_2 Test Stand**

Location of Test: **Lab C** Date and Time: **11 a.m. May 25, 2011**

Hazards Involved: **1.) Overpressure of pipe.**
2.) Sudden release of pressure.
3.) Pressure regulator failure.

Safety Precautions Taken: **1). Burst disks in place on piping**
2.) Eye protection worn during test.
3.) Personnel monitoring cylinder ready to shut off supply.

Special Conditions or Requirements: **None**

Qualified Person / Test Coordinator: **Erik Voirin** Dept/Date: **PPD / May 25, 2011**

Division/Section Safety Officer **Eric McHugh** Dept/Date: **PPD / May 25, 2011**

Results: **Pass – System held pressure of 300 psig for 10 minutes**

Witness **Mark Shoun** Dept/Date **PPD May 25, 2011**

(Safety Officer or Designee)
* Must be signed by division/section safety officer prior to conducting test. It is the responsibility of the test coordinator to obtain signatures.

11. References

1. International Institute of Refrigeration. "Classification of Refrigerants." Web. 26 Apr. 2011. <http://www.iifiir.org/en/doc/1034.pdf>

2. Copper Development Association. "Copper Tube Handbook" Web. 26 Apr. 2011. <http://www.copper.org/publications/pub_list/pdf/copper_tube_handbook.pdf>

3. http://www.cmctechnologies.com.au/marston_bursting_discs%20-%20technical%20guide.pdf

4. ASME. "SELECTING APPLICABLE B31 PIPING CODE SECTIONS." Web. 2 May 2011. < http://cstools.asme.org/csconnect/pdf/CommitteeFiles/22855.pdf >

Appendix A – Relief Device Calculations

Calculations for relief devices

Overpressure Scenario Check List (API 521)

1. Closed outlets - N/A - Closed outlets are not possible except for failure or plugging of the Expansion Valve. The available supply pressure is less than MAWP pressure.
   Coolant failure - N/A.
3. Top reflux failure - N/A.
4. Side reflux failure - N/A
5. Lean Oil failure to absorber - N/A.
6. Accumulation of noncondensables - N/A,
7. Entrance of highly volatile material - N/A.
8. Overfilling - N/A - Overfilling is possible but is not a source of overpressure The available supply pressure less than MAWP pressure.
9. Control Failure - N/A - Refrigeration cycle
10. Abnormal heat or vapor input - N/A - worst case would be item 15
11. **Split exchanger tube - Possible, breakage in heat exchanger tube with high pressure (1200 psi) Carbon Dioxide on shell side.**
12. Internal explosion - N/A
13. Chemical reaction - N/A - Carbon dioxide and R-404 will not react.
14. Hydraulic expansion - N/A - no blocked in areas which can not accommodate the systems fu liquid capacity
15. **Exterior fire - Possible, though would have to be an entire building fire as the piping is routed high above the floor away from small quantities of flammables (box/papers) which could be sources of fires near the piping.**
16. Power failure (steam, electric, air, other) - N/A - system stable at ambient temperatures.

Item 11, and 15 above are identified as possible sources of overpressure.

Item 11 requires a relief rate of 1.178 kg/s $CO_{2:}$

(Disk Capable of 1.224 kg/s CO_2)

- SUFFICIENT FLOW

Item 15 requires an equivalent rating of 1011 SCFM of air for supply side and 0.086 kg/second flow of R404 for Return side:

(Disks Capable of 1096 SCFM of air, and 2.85 kg/sec R404a.)

- SUFFICIENT FLOW

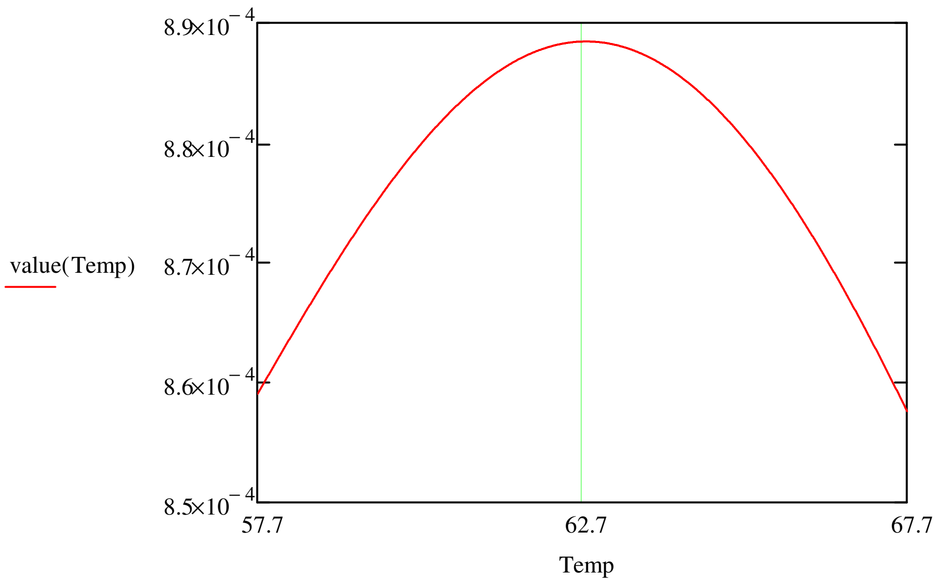
Evaluation of Overpressure Scenario 11- Split heat exchanger tube (assume CO_2 is at maximum pressure (1200 psi) for a worst case scenario)

According to Compressed gas association, the critical temperature for which calculations should be made for relieving a supercritical fluid are when: $\dfrac{\sqrt{v}}{v\cdot\left(\dfrac{\delta h}{\delta v_p}\right)}$ is at a maximum. CGA states at 200 psia the maximum value for hydrogen occurs at 62.7R. A Calculation method will be tested against hydrogen's given value to test for accuracy of the method.

$$dh_{dv}(Temp) := -0.514512683Temp^3 + 110.595964Temp^2 - 7937.122633Temp + 193723.0553$$

$$rootV(Temp) := -0.0002Temp^2 + 0.0345Temp - 1.0974$$

$$value(Temp) := \frac{1}{\left[\left(dh_{dv}(Temp)\right)\cdot(rootV(Temp))\right]}$$

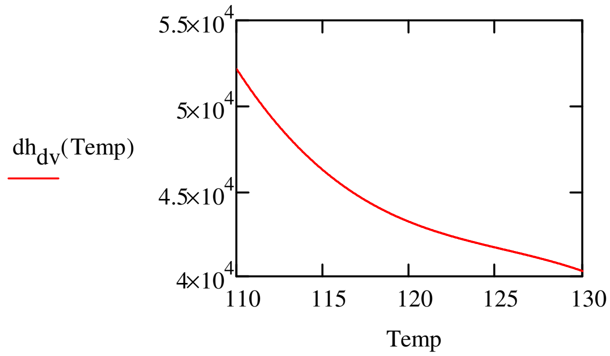


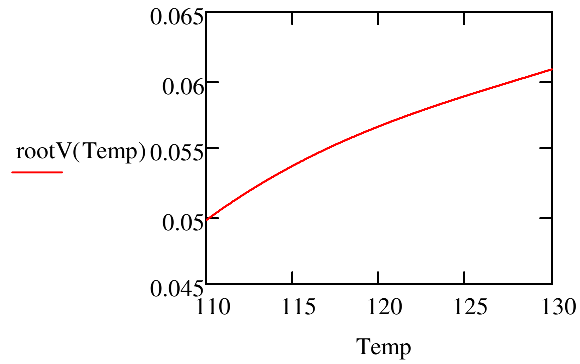
Method Works and is consistent with hydrogen gas value from Compressed gas association. The same method will be used to find the relief valve calculation Temperature of Carbon Dioxide at 1200 psi

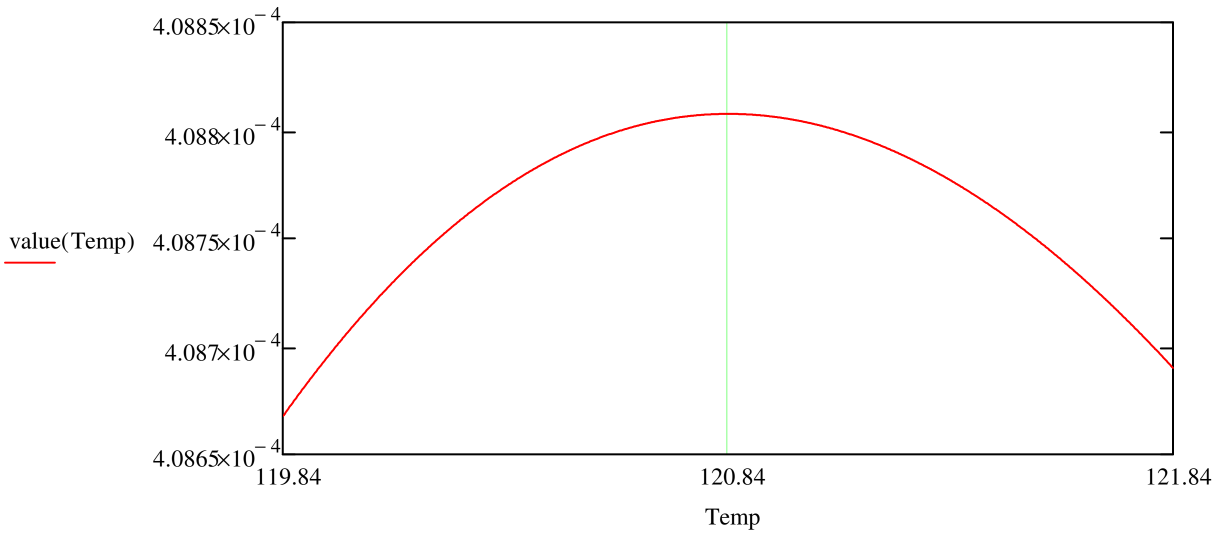
$$dh_{dv}(Temp) := -1.846799534\cdot Temp^3 + 695.2825211Temp^2 - 87493.47076Temp + 3721622.95$$

$$rootV(Temp) := 5.39422\cdot 10^{-7}Temp^3 - 0.000207814Temp^2 + 0.027073145Temp - 1.131746719$$

$$value(Temp) := \frac{1}{\left[\left(dh_{dv}(Temp)\right)\cdot(rootV(Temp))\right]}$$







Temperature for Supercritical fluid relief calculations will be made using this temperature of 120.84 F.

Carbon Dioxide will be analyzed under this scenario since it will be the fluid exiting in the event of a ruptured heat exchanger tube.

Equation 3.1 for sonic flow of relief valve

$$A = \frac{W\cdot\sqrt{T}\cdot\sqrt{Z}}{C\cdot K_1\cdot P_1\cdot K_b\cdot\sqrt{M}} \text{ solve}, W \;\rightarrow\; \frac{A\cdot C\cdot K_1\cdot K_b\cdot\sqrt{M}\cdot P_1}{\sqrt{T}\cdot\sqrt{Z}}$$

Diameter and Area of Heat Exchanger tube orifice

$$d_{tube} := 0.375in - 2\cdot(0.05in) \qquad A_{tube} := \frac{\pi}{4}\cdot d_{tube}^{\;2} = 0.059\cdot in^2$$

Unitless Area

$$A_{tubeU} := \frac{A_{tube}}{in^2}$$

Diameter and Area of Burst Disk Orifice

$$\rho_{1200} := 237.68\frac{kg}{m^3} \qquad A_{orifice} := 0.19in^2$$

Unitless Area

$$A_{orificeU} := \frac{A_{orifice}}{in^2}$$

High Pressure

$$P_{high} := \frac{1214.3psi}{psi}$$

Relief Pressure

$$P_R := \frac{(425 + 14.3)\cdot psi}{psi}\cdot 1.10 = 483.23$$

Value from Fig 3.3 Molar Mass Compressibility from Ref Prop Abs. Temp

$K_b := 1.0$ $M := 44.01$ $Z := 0.57133$ $T := 120.64 + 460$

Value from Fig 3.2 Coefficient of Discharge

$C := 356$ $K_1 := 0.816$

$$FlowRelief := \frac{A_{orificeU} \cdot C \cdot K_1 \cdot K_b \cdot \sqrt{M} \cdot P_R}{\sqrt{T} \cdot \sqrt{Z}} \cdot \frac{lb}{hr} = 1.224 \frac{kg}{s}$$

This should be what our relief valve is capable of relieving at 483 psi

Flow through our Heat Exchanger tube orifice is calculated as:

$$Flow_{tubeMax} := \frac{A_{tubeU} \cdot C \cdot K_1 \cdot K_b \cdot \sqrt{M} \cdot P_{high}}{\sqrt{T} \cdot \sqrt{Z}} \cdot \frac{lb}{hr} = 0.962 \frac{kg}{s}$$

Worst case if relieving to atmosphere not into 425 psi piping system

$$Flow_{tubeMax2} := \frac{A_{tubeU} \cdot C \cdot (1) \cdot K_b \cdot \sqrt{M} \cdot P_{high}}{\sqrt{T} \cdot \sqrt{Z}} \cdot \frac{lb}{hr} = 1.178 \frac{kg}{s}$$

Worst case if relieving to atmosphere not into 425 psi piping system and coefficient of discharge is 1

We can see our Rupture Disk has enough capacity to keep the system from over pressurization in the event of a fully open tube rupture at (1200 + 14.3) psia.

Evaluation of Overpressure Scenario 15 - Exterior Fire

Calculate relief rate based on a blocked in fire scenario, due to certain physical properties (dynamic viscosity) of R-404a being unavailable at relieving conditions, methods of CGA S-1.3-2005 are used in the fire case, which do not employ this material property.

Rupture Disk Set Pressure (at relieving conditions)

$P_{set} := (400 + 14.3)psi \cdot 121\%$

Equivalent Length of Longest length of pipe Blocked in pipe Vessel

$L_E := 100ft$

Largest Suction Tube OD:

$D_{suc} := 1.375in$

Largest Supply Tube OD:

$D_{sup} := 0.5in$

Total Surface Area (Neglect insulation):

$$Pipe_{area} := \frac{\pi \cdot D_{suc} \cdot L_E}{ft^2} + \frac{\pi \cdot D_{sup} \cdot L_E}{ft^2} = 49.09$$

Molar Mass

$M := 97.604$

Correction Factor

$F := 1$

Heat of Vaporization

$$h_{fg} := 30.174 \frac{kJ}{kg} \qquad L := \frac{h_{fg}}{\frac{BTU}{lb}}$$

Absolute Temperature

$T := (139 + 460)$

Compressibility Factor

$Z := 1$

Conservative Value listed by CGA

$C := 315$

Density and specific volume of Liquid and Vapor

$$\rho_g := 364.81 \frac{kg}{m^3} \qquad v_g := \frac{1}{\rho_g} \cdot \frac{1}{\frac{ft^3}{lb}}$$

$$\rho_l := 613.88 \frac{kg}{m^3} \qquad v_l := \frac{1}{\rho_l} \cdot \frac{1}{\frac{ft^3}{lb}}$$

$$G_u := \frac{633000}{C \cdot L} \cdot \frac{v_g - v_l}{v_g} \cdot \sqrt{\frac{Z \cdot T}{M}} = 155.7$$

Required equivilent relief flow of air at standard conditions

$$Q_a := F \cdot G_u \cdot Pipe_{area}{}^{0.82} \cdot \frac{ft^3}{min} = 3792 \cdot \frac{ft^3}{min}$$

Diameter and Area of Burst Disk Orifice

$$\rho_{airSTD} := 1.16 \frac{kg}{m^3} \qquad A_{orifice} := 0.19in^2$$

Unitless Area

$$A_{orificeU} := \frac{A_{orifice}}{in^2}$$

Relief Pressure

$$P_R := \frac{(425 + 14.3)\cdot psi}{psi}\cdot 1.21 = 531.553$$

Number of Burst Disks

$$n_{BD} := 2$$

Value from Fig 3.3

$$K_b := 1.0$$

Molar Mass

$$M := 28$$

Compressibility from Ref Prop

$$Z := 0.99$$

Abs. Temp

$$T := \frac{344.36K}{R} = 619.848$$

Value from Fig 3.2

$$C := 356$$

Coefficient of Discharge
(from reference 5)

$$K_1 := 0.62$$

$$FlowRelief := n_{BD}\cdot\frac{A_{orificeU}\cdot C\cdot K_1\cdot K_b\cdot\sqrt{M}\cdot P_R}{\sqrt{T}\cdot\sqrt{Z}}\cdot\frac{lb}{hr} = 1.2\frac{kg}{s}$$

This should be what our disks are capable of relieving at 531.5 psi

$$VolFlowRelief := \frac{FlowRelief}{\rho_{airSTD}} = 2192\cdot\frac{ft^3}{min}$$

$$Q_a = 3792\cdot\frac{ft^3}{min} \qquad VolFlowRelief < Q_a$$

We can see our Rupture Disk does not have enough capacity to keep the system from over pressurization in the event of an entire building fire, without the benifit of pipe insulation.

Determination of Insulation Credit (per API 521 5.15.5.4)

$$Pipe_{return} := \frac{\pi\cdot D_{suc}\cdot L_E}{ft^2} = 36$$

$$Pipe_{supply} := \frac{\pi\cdot D_{sup}\cdot L_E}{ft^2} = 13.09$$

Insulation Thermal Conductivity (ambient conditions)

$$k_{ins.ambient} := 0.034\cdot\frac{W}{m\cdot K}$$

Insulation Thickness

$$Insul_{Th} := 0.75in \qquad T_{in} := T\cdot R = 344.36\,K$$

API Calculation for F,
with units added to factor for unit consistency

$$F := \frac{k_{ins.ambient}\cdot\left[(904 + 273.15)K - T_{in}\right]}{66570\cdot\frac{kg}{s^3}\cdot Insul_{Th}} = 0.0223$$

API 521 eq. 13
sect. 5.15.5.4
The implied units of the API conversion factor are kg/sec^3.

Required Relief Rate for scenario 15 - Exterior Fire

$$Q_{return} := 21000\cdot\left(\frac{BTU}{hr}\right)\cdot F\cdot\left(Pipe_{return}\right)^{0.82} = 2595\,W$$

Equation from API 521

This energy input to the suction side would boil off a mass of:

$$mass_{boiled} := \frac{Q_{return}}{h_{fg}} = 0.086\,\frac{kg}{s}$$

Value from Fig 3.3 — $K_b := 1.0$

Molar Mass — $M := 97.604$

Compressibility from Ref Prop — $Z := 0.15247$

Abs. Temp — $T := \frac{344.36K}{R} = 619.848$

Value from Fig 3.2 — $C := 356$

Coefficient of Discharge (from reference 5) — $K_1 := 0.62$

$k := 2.1087$ $\quad P := P_R$ $\quad P_{cf} := P\cdot\left(\frac{2}{k+1}\right)^{\frac{k}{k+1}} = 394.108$ $\quad r := \frac{P_{cf}}{P}$ $\quad A := 0.19$

$$FlowRelief_{R404} := \frac{735\cdot A\cdot K_1\cdot\sqrt{\frac{k\cdot r^{\frac{2}{k}}\cdot\left(r^{\frac{k-1}{k}}-1\right)}{(k-1)\cdot(r-1)}}}{\sqrt{\frac{T\cdot Z}{M\cdot P\cdot\left(P-P_{cf}\right)}}}\cdot\frac{lb}{hr} = 2.691\,\frac{kg}{s}$$

Eq. from API-RP520

Many times greater than the required amount, insulation makes a large difference in required flow.

Using the previously uninsulated values for the uninsulated supply lines we get an additional flc requirement of:

$$Q_{a\_supply} := Q_a\cdot\frac{Pipe_{supply}}{Pipe_{return}+Pipe_{supply}} = 1011\cdot\frac{ft^3}{min}$$

$$FlowRelief_{supply} := \frac{VolFlowRelief}{2} = 1096\cdot\frac{ft^3}{min}$$

$FlowRelief_{R404} > mass_{boiled}$

$FlowRelief_{supply} > Q_{supply}$

Devices sufficient on both lines